

Internal Phosphorus Loading in a Shallow
Eutrophic Lake (Journal Version)

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INTERNAL PHOSPHORUS LOADING IN A SHALLOW EUTROPHIC LAKE

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Abstract—Internal loading of phosphorus has been implicated as a major eutrophicating factor in Long Lake, Washington (Kitsap County). As a result of such loading, summer total phosphorus concentrations approach or exceed $100 \mu\text{g P l}^{-1}$. Most of the summer loading of phosphorus is thought to have been released directly from the rich, flocculent sediment in the mid and northern part of the lake as a result of high pH (up to 10) related to phytoplankton photosynthesis. The lake also supports a dense submersed macrophyte crop (areal weighted mean dry weight of about 220 g m^{-2}) composed primarily of *Elodea densa*. Although excretion of phosphorus from healthy *E. densa* was found to be minimal, the potential contribution of P indirectly from sediment via macrophyte uptake and subsequent decomposition in the winter was on the order of $200\text{--}400 \text{ kg yr}^{-1}$ or about 25–50% of the external loading. Nevertheless, loading of phosphorus during predrawdown summers is thought to have originated largely as a direct release from sediment due to high pH. Estimates of sediment phosphorus release determined from laboratory experiments, mass balance and core analyses ranged from 2.2 to $5.6 \text{ mg m}^{-2} \text{ day}^{-1}$.

As a component of the restoration program, the lake (mean depth of 2 m) was drawn down nearly 2 m for 4 months during the summer and fall of 1979. The lake's trophic status was expected to improve due to sediment consolidation and/or macrophyte reduction. The drawdown resulted in an 84% reduction in macrophyte biomass in 1980 but minimal sediment consolidation (0.1 m). Winter decomposition of the much smaller macrophyte crop, apparently provided insufficient phosphorus in the spring to stimulate phytoplankton and to enrich midlake sediments, which has probably occurred in previous years. Low water column pH during the postdrawdown summer of 1980 resulted from relatively low rates of plankton photosynthesis. During the summer of 1980 internal loading of phosphorus was reduced and total phosphorus remained below $50 \mu\text{g l}^{-1}$.

INTRODUCTION

Internal loading of nutrients in lakes has been shown to decrease the effectiveness of restoration measures which are aimed at controlling external inputs (Bjork *et al.*, 1972; Ahlgren, 1977; Welch, 1977; Cooke *et al.*, 1978). Long Lake in western Washington has had high rates of internal phosphorus loading in the summer with the total phosphorus concentration often exceeding $100 \mu\text{g l}^{-1}$ (Perkins *et al.*, 1979). A large macrophyte crop consisting primarily of *Elodea densa* has covered approx. 40% of the lake with a mean whole lake biomass of approx. $220 \text{ g dry weight m}^{-2}$ (Welch *et al.*, 1979).

Recreational use has been limited due to the dense blooms of blue-green algae (*Aphanizomenon*, *Anabaena*, *Gleotrichia* and *Coelosphaerium*) and to the thick stands of macrophytes. The greatest density of macrophytes (*Elodea densa*, as well as *Nymphaea odorata* and *Nuphar polysepalum*) occurs over the southern part of the lake (Hufschmidt, 1978). As a result of impaired recreational use, a restoration program was initiated in 1976. Drawdown was one of several techniques proposed. It was hoped that drawdown would restore the lake by reducing macrophytes and compacting sediment. The lake level was drawn down nearly 2 m during June through October 1979. The major lake area affected by the drawdown was the southern part. The lake was then treated with

alum during September 1980, 1 yr after the drawdown. The effects of the alum treatment on lake water quality will be assessed in a later paper.

Aquatic macrophytes and lake sediment have been commonly implicated as sources of phosphorus loading in lakes. The macrophyte crop in Long Lake was previously examined as a potential source of the internal phosphorus load (Gabrielson, 1977; Welch *et al.*, 1979). Macrophytes have been shown to release phosphorus to the water column by excretion during growth (McRoy *et al.*, 1972). Radiotracer experiments performed by Gabrielson (1977) indicated no net release of phosphorus by excretion from healthy *Elodea densa* cultured from Long Lake. Release through sloughing or during senescence and decomposition has been considered a more likely pathway (Kistritz, 1978; Landers & Frey, 1980; Prentki, 1979). Although decomposing macrophytes may supply substantial amounts of phosphorus to the lake during winter die-back (Welch *et al.*, 1979), direct release from sediment may be more important in Long Lake (Jacoby, 1981).

The importance of pH in controlling phosphorus equilibria in sediments has been demonstrated in several studies (MacPherson *et al.*, 1958; Lijklema, 1976; Anderson, 1974). The potential contribution of phosphorus from rich, flocculent Long Lake sediment at high pH is assessed in this work. The effects of drawdown on the macrophyte crop and consequently phosphorus cycling helped clarify the roles of macro-

phyte decomposition and sediment release of phosphorus in this lake. This paper discusses the respective roles of these two processes in contributing to high phosphorus and algal content during the summer in a shallow, eutrophic lake.

METHODS

The 137 ha lake has a mean depth of only 2 m and a rather high flushing rate ranging from 3.6 to 8.0 yr⁻¹ (Fig. 1). It is a soft-water lake with alkalinity ranging from 20 to 40 mg l⁻¹ as CaCO₃. High pH (8–10) is found in the summer as a result of its low buffering capacity and high rates of primary productivity. Salmonberry Creek is the major inlet stream (approx. 60% of total input) and Curley Creek is the outlet. Small ungauged inlets exist at the south end.

Internal loading calculations

Short-term water and P budgets calculated for 4 yr (1976–1980) were used to indicate the occurrence and extent of internal loading of P in Long Lake. Net sedimentation or release of P in kg for a given time period was determined for the following mass balance equation:

$$S = O + \Delta P - IS - IU - G - ASL$$

where S is net sedimentation or release, O is Curley Creek outflow, ΔP is change in lake P, IS is Salmonberry Creek inflow, IU is ungauged surface inflow, G is groundwater, and ASL is the combined input of bulk atmospheric deposition and lakeside septic tank leachate.

The time steps averaged about two weeks and correspond to the intervals between sampling trips. The P concentrations determined in the lake and gauged and ungauged streams at the start and end of each time step interval were used to calculate the balance. The P concentration in groundwaters was taken as 120 $\mu\text{g l}^{-1}$, an average determined from seepage meters (Lee, 1977) placed around the lake during 1976–1977. The concentration in ungauged runoff was assumed to be represented by two ungauged streams, which were monitored every 2 weeks.

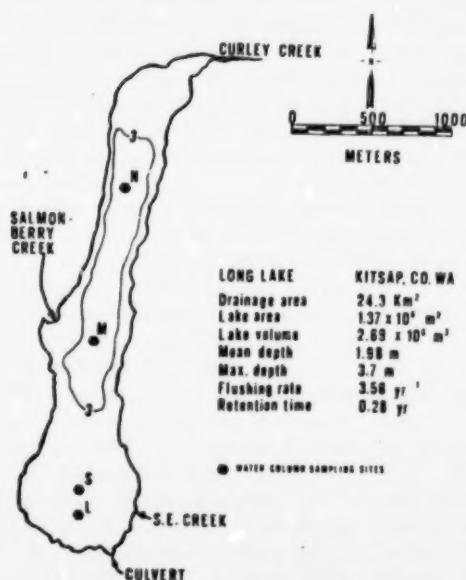


Fig. 1. Water column sampling locations and morphometric characteristics of Long Lake. N, M, S and L refer to North, Mid, South and Lilies (Perkins *et al.*, 1979).

Determinations on several small inlets following a storm compared closely to those in the regularly sampled streams. The combined loading rate from bulk atmospheric deposition (44%) and lakeside septic tanks (56%) was assumed to remain constant. The former is based on rain fall determinations made 5 km from the lake (Johnson *et al.*, 1966) and using a factor of 1.5 to convert soluble to total P (Ruppert, 1975). The estimate for septic tank leachate is based on a *per capita* loading rate of 0.88 kg yr⁻¹ and an 80% soil retention factor (Gilliom, 1978). These two inputs were lumped together for each time period calculation using a rate of 0.52 kg day⁻¹.

Continuous stage recorders, located on the major inlet and outlet of the lake were used to estimate inflow, outflow, and quantity of water in the lake during each time step. Precipitation and evaporation rates were obtained from recordings at nearby Kitsap County Airport. Ungauged surface and groundwater inflows were determined by difference in balancing the water budget. Because independent estimates of groundwater inflow were considered unreliable the two sources were divided in the water budget by the following assumptions:

1. When the inflow from the ungauged catchment, as calculated by difference, was equivalent to 50% of the Salmonberry Creek inflow, it was attributed all to surface inflow. Groundwater input was assumed to be effectively zero.
2. When the input from the ungauged catchment dropped below an amount equivalent to 50% of the Salmonberry Creek contribution for a particular time interval, it was assumed that the surface inflow from the ungauged catchment was 50% of Salmonberry Creek and that groundwater recharge from the lake accounted for the observed discrepancy.
3. When the inflow from the ungauged catchment exceeded 50% of Salmonberry Creek (e.g. during wet periods), it was assumed that the surface inflow equalled 50% of Salmonberry Creek plus one-half of the amount in excess of 50%. Groundwater input was assumed to account for the other half of this excess.

In vitro sediment experiments

The P content of the sediments from the North and South part of the lake at Stas M and L was fractionated into its various components from core samples taken on 14 April 1978. Sediment character varied little throughout the lake with differences between M and L being mainly depth and macrophyte density. The purpose of the core sampling was to determine the important forms of P in the sediment and how these varied with sediment depth and lake location. On 4 August 1978, cores were again collected and the sediments fractionated so that a comparison could be made between the sediments before and during a period of extensive internal P loading. The cores were sectioned every centimeter. The fractionation method used was a modification by Williams *et al.* (1967) of the serial fractionation procedure developed by Chang & Jackson (1958). The NH₄Cl, NH₄F, 0.1 N NaOH and the citrate dithionate fractions were all combined into a single available inorganic P fraction and referred to as AI-P. Available inorganic P is that pool of P believed to be potentially exchanged with overlying water or available for plant uptake.

Two *in vitro* experiments were performed to determine the effect of pH on the equilibrium concentration of P in a sediment-water system using sediment from Stas M and L. In the first experiment 4 ml of wet surface (upper 5 cm) sediment was mixed with 36 ml of distilled water in a 50 ml centrifuge tube and allowed to equilibrate for 24 h on a shaker table. The pH was adjusted over the range of 4–10 with 0.1 N NaOH or 0.1 N HCl in 15 identical subsamples of the sediment mixtures from Stas N and S. Light was

excluded and the temperature maintained at 24°C. Aerobic conditions were maintained in the stoppered centrifuge tubes by bubbling them with air after 12 h. Upon termination, the samples were centrifuged for 30 min at 1700 rev/min⁻¹. The supernatant was drawn off, filtered through a 0.45 µm pore size Millipore (HA) and analyzed for TDP (total dissolved P) using the ascorbic acid molybdenum blue method (APHA, 1975), following digestion with acid persulfate.

In the second experiment, sediment was collected from Sta. S and placed in three plexiglass chambers. The sediment was allowed to compact by exposure to air for 14 days to attain the same loss in water content as the 1979 lake drawdown. The tanks measured 36 × 20 × 10 cm and held approx. 2 l. of sediment and 7.2 l. of filtered Long Lake water. After 1 month, pH and P levels in the water column had become stable. The pH was then adjusted at about 10 by addition of NaOH and maintained for 55 days. The systems were aerobic and temperature was fairly constant at around 20°C. Measurements of total P (TP), soluble reactive P (SRP), TDP, pH, alkalinity, dissolved oxygen and temperature in the water column were performed at regular intervals during the course of the experiment. Total P, SRP and pH were monitored more frequently while the other constituents were measured at about weekly intervals. SRP was determined by filtering undigested samples through a 0.45 µm pore size (HA) millipore and analyzing for phosphate as described above. Samples for total P and TDP were first digested as described earlier. The rate of P release was calculated as the slope of the line for the time interval over which the rate of P increase was constant and maximum (day 38–81).

Macrophyte surveys

Macrophyte surveys were conducted in Long Lake during periods of peak biomass (August through September) in each year from 1976 through 1980. In addition, during 1978 and 1980 biomass was also determined in June in order to estimate the rate of increase during the growing season. The size of the overwintering crop was also determined from a biomass measurement on 14 March 1979.

Based on depth interval and gradient, four separate sampling areas were defined in the lake. These were designated as South Lilies (<2 m), South (2–3 m), North Shores (<2 m) and Midlake (2–3.5 m). Each area supported a macrophyte community of relatively homogeneous density. Thirty-four to 44 stations were sampled during each of the macrophyte surveys. A cylindrical sampler enclosing 0.255 m² was used to obtain plant samples on a stratified random design (Gabrielson, 1977). Plants were removed from within the area of the sampler by SCUBA diver, washed free of epiphytes and sediment, identified, and then dried at 70°C and weighed. Results were reported as dry weight biomass for the whole lake.

RESULTS AND DISCUSSION

Extent and occurrence of internal loading of P in Long Lake

Short-term water and P budgets were calculated for approx. 2-week intervals from 1976 through 1980. Net flux of P across the sediment–water interface was calculated by difference in the mass balance and is shown for each year in Figs 2–5. Lake water TP concentrations, as volume weighted means, are plotted in the upper graphs in each Figure. During the summer months of 1977 and 1978, TP reached high concentrations approaching or exceeding 100 µg l⁻¹ (Figs 2 and 3). Dense blooms of blue-green algae occurred in

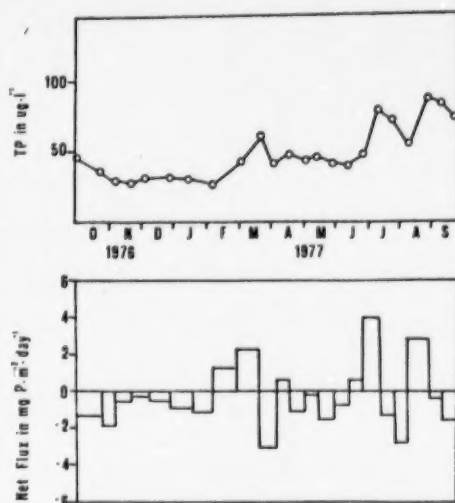


Fig. 2. Volume-weighted lake P concentration and net flux across the sediment–water interface determined by a two week interval P budget during 1976–1977.

association with the high TP. Net internal loading of P was substantial during these periods as indicated by the positive vertical bars associated with peak TP content of the water. Large negative bars during summer probably represent sedimentation of plankton phosphorus following blooms, but differences in rates are no doubt exaggerated by interval selection. Internal P loading almost equalled external loading during the predrawdown summers (2.5–3 months) of 1977 and 1978: 46 and 47% of the total loads, respectively. Summer internal loading was taken as the net change in flux during the 2.5–3 month period.

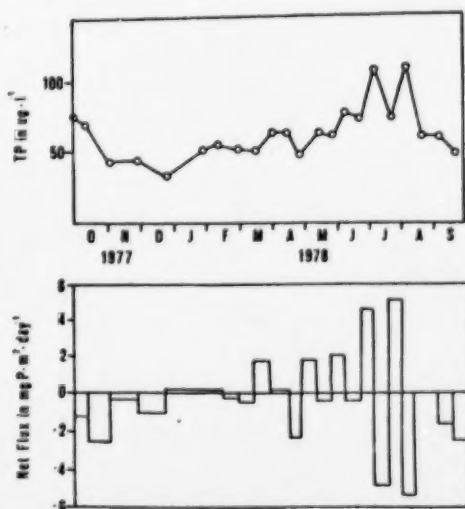


Fig. 3. Volume-weighted lake P concentration and net flux across the sediment–water interface determined by a two week interval P budget during 1977–1978.

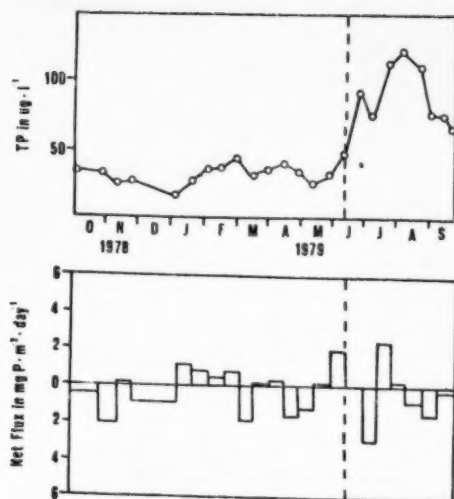


Fig. 4. Volume-weighted lake P concentration and net flux across the sediment-water interface determined by a two week interval P budget during 1978-1979.

During drawdown (Fig. 4) TP content was high although blue-green algal blooms were relatively scarce. Green algae and diatoms were dominant during the drawdown in contrast to previous predrawdown years. Macrophyte tissue was evident along the exposed border of the lake and its decomposition during the summer probably contributed to the high TP content in the water column.

After the drawdown (1980), summer internal loading was substantially reduced (by about 80%) compared to predrawdown rates calculated for 1976-1978. From November 1979 to September 1980, periods

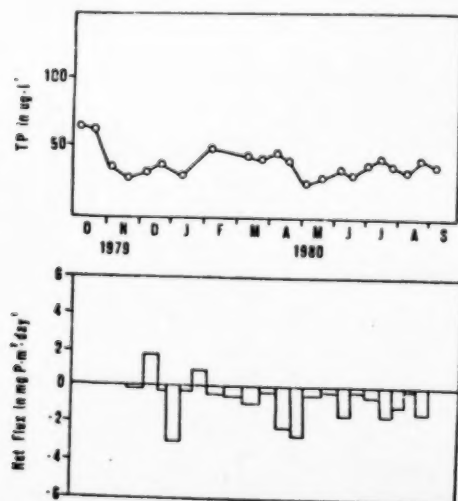


Fig. 5. Volume-weighted lake P concentration and net flux across the sediment-water interface determined by a two week interval P budget during 1979-1980.

Table 1. Summer (June-August) values for TP content (volume-weighted mean) and median and range of all pH observations in Long Lake during 1976-1980

Year	Median pH	pH Range	Mean TP ($\mu\text{g l}^{-1}$)	
1976	9.1	7.1-10.3	58	
1977	9.0	7.2-9.9	61	
1978	8.6	7.0-9.3	76	
1979	7.2	6.6-9.2	83	Drawdown
1980	8.1	5.9-9.0	36	

were few when internal loading could be suspected (Fig. 5). During the summer of 1980, water column mean TP content was approx. 50% lower than during previous summers (Table 1). Furthermore, internal loading was not evident based on the mass balance calculations for any 2-week interval in this period. Correspondingly, dense blue-green algal blooms did not occur.

Although the error in the mass balance estimates of internal loading may be substantial because of assumptions made to handle quantities not determined directly, there is no doubt that internal loading is significant in Long Lake. Furthermore, internal loading of P clearly decreased following drawdown, although the causes for that decrease are not entirely clear. Potential sources from macrophyte decomposition and sediment release will be examined in light of the changes that occurred in the lake following drawdown.

Sediments as the internal P source

Results from P distribution in the lake and sediment core analyses implicate sediments as the major source of internal P loading during the summer. Fractionation of cores taken from Sta. M revealed that AI-P was approx. 5 times higher in the midlake surface sediment than in the southern sediments (L) (Table 2 and Welch *et al.*, 1979). Macrophyte mining of P, a factor in the south where macrophyte biomass is densest, removes AI-P and enriches the organic P fraction in the surface sediment thereby decreasing the AI-P pool. There are also higher inputs of P in the north-to-midlake area because the major inflow and outflow, Salmonberry and Curley Creeks, are located there (Fig. 1). In addition, a net loss of AI-P occurred in the upper 5 cm of sediments at Sta. M during the period of internal P loading. April-August 1978, which was not observed in cores from Sta. L (Table 2). This loss, or apparent release rate, was calculated directly as a difference between the April and August concentrations in the upper 5 cm and amounted to $2.2 \pm 1.1 \text{ mg m}^{-2} \text{ day}^{-1}$. This rate, if extrapolated to the northern lake area as a total sediment loss during the 3-month summer period, agrees well with and helps substantiate internal loading estimates calculated from the P mass balance for the same period (175 vs 154 kg, respectively). No loss was observed at

Table 2. Available inorganic P (AI-P) in $\mu\text{g l}^{-1} \pm 95\%$ CI determined in sediment at two stations in Long Lake by fractionation of core samples

Sediment core depth (cm)	Sta. L 28 Apr 1978	Sta. M 28 Apr 1978	Sta. M 4 Aug 1978
0-2	342 $\pm$ 17	1550 $\pm$ 28	1422 $\pm$ 26
2-5	328 $\pm$ 23	915 $\pm$ 23	880 $\pm$ 23
5-15	287 $\pm$ 18	666 $\pm$ 12	671 $\pm$ 12
15-25	249 $\pm$ 11	437 $\pm$ 9	—
25-35	182 $\pm$ 14	313 $\pm$ 9	—
35-45	163 $\pm$ 12	301 $\pm$ 11	—

Sta. L in the southern lake. From these observations, it would appear that the probable area of sediment P release in the summer is from the deeper ($>3\text{ m}$) northern area and not the southern area where macrophytes are abundant.

Other observations as well implicate the mid-northern area in this role. The horizontal water P gradient in the lake supports the mid-to-northern located sediments as the primary source of internal P loading in the summer. Mean TP content at Stas M and N were almost twice as high as that to the south (S); 51, 71 and $81\text{ }\mu\text{g l}^{-1}$ at M and N combined compared to 26, 46 and $52\text{ }\mu\text{g l}^{-1}$ at S and L during the summers of 1976, 1977 and 1978, respectively. TP content in the southern area was relatively constant throughout the year compared to the northern region which shows wide seasonal fluctuations. The location of the major inflow no doubt affects the distribution of P in the lake. However, external inputs of P are typically low during the summer. Therefore, the summer distribution of TP in the water suggests that incomplete mixing occurs and that the high levels of TP in the mid to north end of the lake do not originate from the southern area via either sediment release or macrophyte sloughing/decomposition.

Mechanism for sediment release of P

Anaerobic release of P is not considered significant in this lake since stratification does not occur and oxygen depletion near the sediment has not been ob-

served. Instead, *in vitro* experiments have indicated that at high pH, substantial release of P occurs from Long Lake sediment. Equilibrium experiments with sediment core samples were performed which demonstrated the effect of pH on the P of the overlying water. As expected, more P was released from mid-lake (M) sediments, which contain higher AI-P levels, than from sediments in the south (L) at the same pH (Fig. 6). The higher release of P from mid-lake at low or high pH agrees well with the results of MacPherson *et al.* (1958) who equilibrated sediment from a wide variety of lakes with water at pH 4-8.

In the *in vitro* experiment where pH was maintained at 10 for 55 days, P rose steadily in a linear fashion and eventually leveled off around $900\text{ }\mu\text{g l}^{-1}$ (Fig. 7). The net rate of P released was determined from the slope of the line and was $5.6\text{ mg m}^{-2}\text{ day}^{-1}$. The compacted south end sediment used in this experiment contained a lower AI-P pool than the north or mid-lake sediments. An even higher release rate of P could be expected from northern and midlake sediments, which were not compacted during drawdown.

The mechanism by which the equilibrium concentration of SRP increases at high pH is believed to occur as the hydroxyl ions are exchanged for phosphate on amorphous iron and aluminum gel complexes (Lijklema, 1976; Stumm & Morgan, 1975). The importance of the degree of water-sediment contact in the extraction of phosphate from sediment has been stressed by Lijklema (1976). Such contact is a

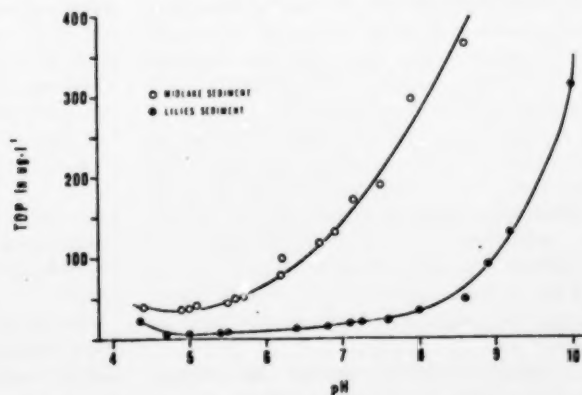


Fig. 6. Concentration of total dissolved phosphorus in water following 24 h equilibration with sediment from two stations (M and L) in Long Lake over a gradient of pH.

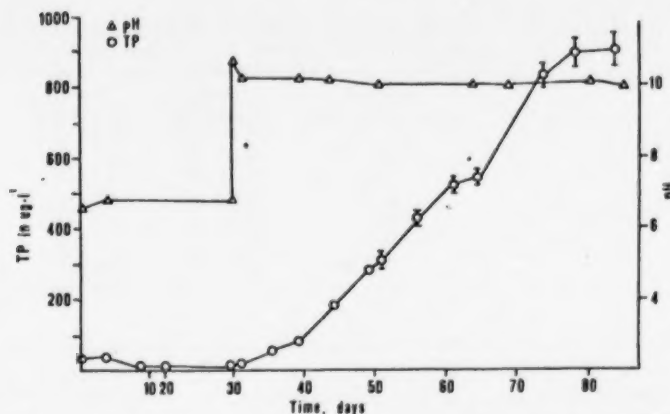


Fig. 7. Release of P from Long Lake sediment following an increase and maintenance of the pH at 10. Rate of release was determined from day 38 to 81. Values are means of 3 replicates $\pm$ 1 SE.

function of the hydrodynamic condition and compactness of the sediment. In shallow lakes, such as Long Lake, the surface layers of the flocculent sediment have a greater tendency to come in contact with water of high pH than in a deeper, stratified lake (Lijklema, 1976).

Lake pH and TP

Because high pH was maintained by high rates of photosynthesis for extended periods of time in the summer, direct release of P from the sediments probably represents a substantial contribution to internal P loading in this lake. Anderson (1974) also suggested that the liberation of phosphate in summer from the sediment of six shallow Danish lakes could be due to photosynthetically caused high pH (up to 10.5).

Periods of high TP and chlorophyll *a* content coincide with high pH during the summers of 1976, 1977 and 1978 (Fig. 8). In June through August of 1979–1978, pH and TP content remained consistently high (see also Table 2 and Fig. 8). High TP and low pH during the drawdown summer would appear to be anomalous. However, the lake-level drawdown resulted in atypical summer conditions. Blue-green algal blooms were reduced, along with photosynthetic activity during the period. As a result, pH was lower which would have provided little potential for sediment release of P by that mechanism. Instead, the high P content can probably be accounted for by the extensive macrophyte decomposition observed at this time and less volume in the lake to dilute the sediment-released P. During the summer of 1980, following the drawdown, algal blooms and associated photosynthetic rates were reduced resulting in a lower median pH of only 8.1 (Table 2 and Fig. 8). Correspondingly, TP content was also about 50% less than during predrawdown summers.

The drawdown primarily affected the southern shallow (<2 m) area of the lake. Sediment compaction was determined to be only 9 cm in depth. The

lower photosynthetic rates and therefore lower pH following drawdown cannot be explained by sediment compaction since the primary source of summer internal P release is considered to be represented by mid-northern sediments. The effect of drawdown on the macrophyte crop probably led indirectly to the decrease in lake water P content and improved lake quality the year following lake refilling (1980).

Aquatic macrophytes as an internal P source

The amount of P potentially released to the water column by decomposing macrophytes in Long Lake in the winter was estimated at between 200 and 400 kg yr⁻¹ (Perkins *et al.*, 1979; Welch *et al.*, 1979). This P is either retained in the water column or deposited on the sediment surface. Thus, the macrophytes may be (directly through decomposition or indirectly through surface sediment enrichment) increasing the amount of P available in the lake water.

During the winter months of the three predrawdown years, macrophyte decomposition probably supplied substantial quantities of P to the water column. This was characterized by increases in mean water column P during late winter–spring (Figs 3, 4 and 5). In support of this, water column TP in the dense macrophyte stands at Stas S and L during the winter was almost twice that in the northern areas of the lake where macrophyte density was much less (55 vs 30 µg l⁻¹).

During the summer of the drawdown, decomposing macrophytes no doubt contributed much P to the lake. Although this was primarily a function of the drawdown and not a normal dieback, the resulting TP increase demonstrates the macrophyte potential for internal loading of P in this lake.

Drawdown had a substantial impact on macrophyte biomass. Weather during the drawdown was hot and dry, and thus ideal for maximum macrophyte elimination. *E. densa* rooted in exposed sediments over 40% of the lake area died through desiccation.

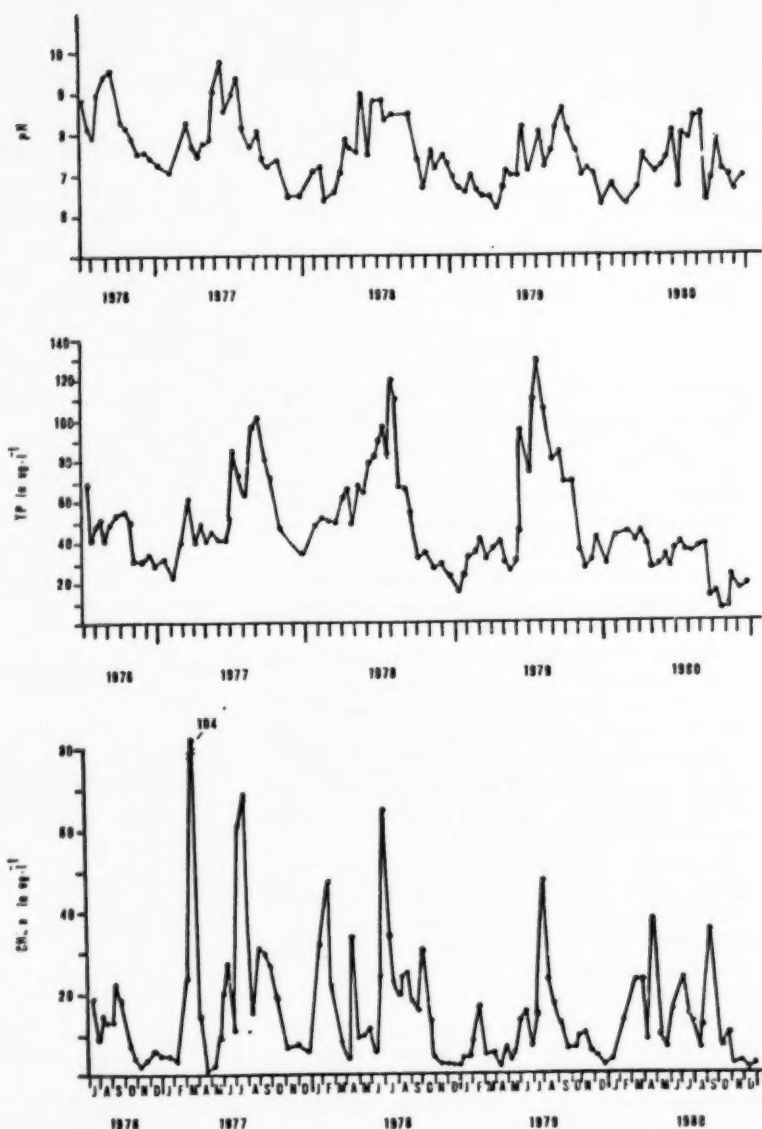


Fig. 8. Chlorophyll *a*, total phosphorus and pH levels for combined north and mid area of Long Lake, 1976–1980.

However, the *Nymphaea* and *Nuphar* were not affected by exposure and remained green throughout the drawdown period. Their extensive root system apparently permitted adequate water uptake. The areal weighted mean dry weight biomass of submersed macrophytes was reduced 84%, decreasing from 124 g m^{-2} in June 1978 to 20 g m^{-2} in June of 1980 (Table 3). The quantity of macrophytes overwintering was reduced in 1980 after the drawdown, therefore the amount of P released from plants decomposing during the winter was no doubt proportionately less. Less P would then be available for phytoplankton use in the spring as well as enrichment of midlake sediments. By August 1980, the crop had increased over 4-fold

from 20 to 87 g m^{-2} . This would amount to only a 50% reduction relative to the August 1978 predrawdown crop. The rate of macrophyte recolonization was rapid in the exposed areas and it is expected that macrophyte biomass will achieve predrawdown levels in 1981.

Cause for decreased internal P loading

During the predrawdown years the winter decomposition of macrophytes supplied an initial input of P to lake water contributing to spring algal blooms as well as an annual enrichment of the mid lake sediments. Provided with P from winter macrophyte decomposition, phytoplankton maintained high photo-

Table 3. Area-weighted means of macrophyte biomass for 1976-1980 in Long Lake (g dry wt m⁻² ± 95% CI)

Station (% of total lake area)	No. of samples	9/76	10/77	6/28/78	8/24/78	3/14/79	6/26/80 27	8/23/80 24
South Lilies (18%)	6	347 ± 125	413 ± 73	366 ± 78	498 ± 54	87 ± 15	6 ± 13	62 ± 57
South (17%)	8	303 ± 83	168 ± 37	191 ± 43	240 ± 76	19 ± 12	29 ± 20	177 ± 73
North Shore (14%)	8	149 ± 93	120 ± 50	104 ± 70	129 ± 71	50 ± 31	29 ± 20	74 ± 45
Midlake (51%)	12	211 ± 93	91 ± 54	22 ± 13	24 ± 13	6 ± 5	19 ± 10	70 ± 36
Lake Weighted Mean		242 ± 97	166 ± 54	124 ± 38	160 ± 39	29 ± 12	20 ± 14	87 ± 47

synthetic rates throughout the summer resulting in high pH. Under conditions of high pH the sediment may then act as the major internal source of P causing still higher photosynthetic rates and high pH. During the drawdown summer (1979), sediment release of P by that mechanism was probably insignificant because pH remained rather low. The high TP content observed was probably contributed to by the decomposition of exposed macrophytes as well as a concentrating effect of reduced volume.

After the drawdown, the initial supply of late winter P had decreased as a result of the macrophyte reduction, which in turn would have slowed primary productivity early in the growing season and decreased enrichment of midlake sediments. The reduced available P, primary productivity and pH during the spring and summer, would have resulted in a decreased release of P from sediments.

In summary, the drawdown of 1979 helped clarify the role of the sediment and aquatic macrophytes as sources of internal P loading in Long Lake. The principal impact was on the macrophyte crop. Sediment compaction was minimal and only occurred in the shallow areas of the lake believed to be of minor importance in terms of sediment release of P. Oxidation of the sediment surface exposed during drawdown is probably not a plausible explanation for the decrease in internal loading because most of the area exposed was in the southern and shallowest area, which is believed to be least important for sediment release. Therefore, the reduction in TP levels in 1980 was largely due to the reduction in the macrophyte crop. However, since the rate of macrophyte recolonization was rapid, the beneficial effects of the drawdown are likely to be short term.

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REFERENCES

- Ahlgren I. (1977) Role of sediments in the process of recovery of an eutrophicated lake. In *Interaction Between Sediments and Freshwater* (Edited by Golterman H. L.), 473 pp. Proceedings of an International Symposium, Amsterdam, Netherlands. Junk, The Netherlands.
- Anderson J. M. (1974) Nitrogen and phosphorus budgets and the role of sediments in six shallow Danish lakes. *Archs Hydrobiol.* 74, 428-550.
- APHA (1975) *Standard Methods for the Examination of Water and Wastewater*, 14th Edition. 1193 pp. Washington, DC.
- Björk S. *et al.* (1972) Ecosystem studies in connection with the restoration of lakes. *Verh. Int. Verein. Limnol.* 18, 379-387.
- Chang S. C. & Jackson M. L. (1957) Fractionation of soil phosphorus. *Soil Sci.* 84, 133-144.
- Gabrielson J. O. (1977) The role of macrophytes in the phosphorus budget of Long Lake. 82 pp. M.S. Thesis, University of Washington.
- Gilliom R. J. (1978) A simple model for estimating lake eutrophication impacts for watershed landuse. M.S. Thesis, University of Washington.
- Hufschmidt P. W. (1978) Interactions between macrophytes and phytoplankton in Long Lake. 88 pp. M.S. Thesis, University of Washington.
- Jacoby J. M. (1981) Lake phosphorus cycling as influenced by drawdown and alum addition. 153 pp. M.S. Thesis, University of Washington.
- Johnson R. E., Rossano A. T. Jr & Sylvester R. O. (1966) Dustfall as a source of water quality impairment. *ASCE, SED* 92, 245-267.
- Kistritz R. U. (1978) Recycling of nutrients in an enclosed aquatic community of decomposing macrophytes. *Oikos* 30, 561-569.
- Landers D. H. & Frey D. G. (1980) The dieback role of *Myriophyllum spicatum* in Monroe Reservoir, Indiana. Purdue University Water Research Center Technical Report No. 134, 105 pp.
- Lee D. R. (1977) A device for measuring seepage flux in lakes and estuaries. *Limnol. Oceanogr.* 22, 140-147.
- Lijklema L. (1976) The role of iron in the exchange of phosphate between water and sediments. In *Interactions Between Sediment and Freshwater* (Edited by Golterman H. L.), 473 pp. Proceedings of an International Symposium, Amsterdam, Netherlands. Junk, The Netherlands.
- MacPherson L. B., Sinclair N. R. & Hayes F. R. (1958) Lake water and sediment: III The effect of pH on the partition of inorganic phosphate between water and oxidized mud or its ash. *Limnol. Oceanogr.* 3, 318-326.
- Perkins M. A., Welch E. B. & Gabrielson J. O. (1979) Limnological characteristics of Long Lake, Kitsap

- County, Washington. Limnological and Socioeconomic Evaluation of Lake Restoration Projects: Approaches and Preliminary Results. EPA-600/3-79-005, 96-118.
- Prentki R. T. (1979) Depletion of phosphorus from sediment colonized by *Myriophyllum spicatum*. In *Aquatic Plants, Lake Management and Ecosystem Consequences of Lake Harvesting* (Edited by Breck J. E., Prentki R. T. & Loucks O. L.), 435 pp. Madison, WI.
- Ruppert H. (1975) Geochemical investigation on atmospheric precipitation in a medium sized city (Göttingen, FRG). *Wat. Air Soil Pollut.* **4**, 447-460.
- Stumm W. & Morgan J. J. (1975) *Aquatic Chemistry* 583 pp. Wiley, New York.
- Welch E. B. (1977) Nutrient diversion: Resulting Lake Trophic Status and Phosphorus Dynamics. Ecology Research Series, EPA-600/1, 3-88-003, 91.
- Welch E. B., Perkins M. A., Lynch D. D. & Hufschmidt P. W. (1978) Internal phosphorus related to rooted macrophytes in a shallow lake. In *Aquatic Plants, Lake Management and Ecosystem Consequences of Lake Harvesting* (Edited by Beck J., Prentki R. T. & Loucks O. L.), 435 pp. Madison, WI.
- Williams J. D. H., Syers J. K. & Walker T. W. (1967) Fractionation of soil inorganic phosphate by a modification of Chang and Jackson's procedure. *Soil Sci. Soc. Am. Proc.* **31**, 736-739.